State of California
AIR RESOURCES BOARD

STAFF REPORT

PUBLIC MEETING TO CONSIDER A STATUS REPORT ON CATALYST TESTING OF SPARK-IGNITION INBOARD/STERNDRIVE PLEASURECRAFT

Date of Release: October XX, 2004
Scheduled for Consideration: October 28, 2004
Agenda Item No.: 04-9-3

FOREWORD

This report contains results from emission tests performed on four spark-ignition inboard/sterndrive marine engines, before and after 480 hours of “on-water” operation with a catalyst-equipped exhaust system. As part of the 2001 rulemaking that established catalyst-based exhaust emission standards for inboard and sterndrive engines, the Board directed staff to undertake a joint developmental test program to demonstrate the safeness and durability of catalysts in the marine environment.

Other participants contributing to this project were:

- National Marine Manufacturers Association: providing boats and engines
- Manufacturers of Emission Controls Association: supplying catalysts and emission control support
- United States Coast Guard – Flotilla #74*: safely operating the boats on Canyon Lake

The Southwest Research Institute was contracted by the Air Resources Board to conduct the project, which commenced in August 2002 and was completed by September 2004.

* A special thank you to Ms. Dona Lore, for her generous efforts at Canyon Lake.

Table of Contents

I. Introduction

The purpose of this report is to present the findings of an “on water” catalyst test project for inboard and sterndrive boats. The project was conducted over the 2002-2004 time frame for the purpose of demonstrating the safeness and durability of catalysts and other related emission control components in the marine environment. The report will also inform the Board of recent events that are of importance to the inboard/sterndrive rulemaking.

II. Background

Regulatory activity aimed at controlling exhaust emissions from spark-ignition recreational marine engines is less than ten years old. The United States Environmental Protection Agency (U.S. EPA) first adopted exhaust emission standards for personal watercraft and outboard boat engines in 1996. However, revised emissions inventory modeling showed that the benefits of the federal rulemaking were not sufficient to meet California’s air quality goals. Therefore, the Air Resources Board (the “Board” or “ARB”) adopted exhaust emission regulations for spark-ignition recreational marine engines in 1998. The Board approved regulations that accelerated the 2006 federal standards to begin in 2001 in California. The regulations also set more stringent standards for these engines in 2004 and 2008. By 2008, personal watercraft and outboard engines in California will meet exhaust emission standards that are numerically 65 percent less than federal exhaust emission standards.

Although personal watercraft and outboard boats contributed more emissions, the inventory modeling showed that inboard and sterndrive boats also contributed significantly to ozone-forming emissions in California. Because of this, the Board adopted exhaust emission standards for these vessels in 2001. Beginning with the 2003 model year, manufacturers of inboard and sterndrive engines have been required to demonstrate compliance to standards that are equivalent to California’s 2008 standards for personal watercraft and outboards. During the 2007-2009 time frame, catalyst-based emission standards will be phased-in.

A) Description of Inboards and Sterndrives

Inboard and sterndrive vessels are primarily used for recreation. The engines are most commonly derived from V-8 or V-6 automotive gasoline engines. In the simplest inboard design, the engine drives a long, straight propeller shaft. This is the oldest historical design and it remains popular today. With sterndrive boats, the engine is situated inboard in the extreme rear-end of the boat, with the S-shaped transmission external to the boat.

Another type of propulsion system is the inboard V-drive. It is referred to as a V-drive because the engine is placed at the extreme rear end of the boat but faces backward with the shaft-end toward the front, forming the shape of a "V." This placement allows more room in the boat. The exhaust in this configuration is also routed through the transom.

B) 2001 Rulemaking

Following a public hearing on July 26, 2001, the Board adopted provisions for emission standards, certification, environmental/consumer labeling, on-board diagnostics, and other related requirements to the California regulation governing spark-ignition inboard and sterndrive engines. The emission standards begin with the 2003 model year and later inboard and sterndrive engines. A phase-in schedule for the catalyst-based emission standards was also adopted, beginning with the 2007 model year.

This regulatory action made 2003 and later inboard and sterndrive engines subject to the provisions found in Title 13 of the California Code of Regulations (CCR), Sections 2440-2446. The in-use compliance testing and recall provisions found in CCR Sections 2111-2140 and 2147 apply to 2009 and later inboard and sterndrive engines.

The non-catalyst based emission standard for 2003-2008 model year inboard and sterndrive engines is 16 grams per kilowatt-hour (g/kW-hr) for hydrocarbons plus oxides of nitrogen ($HC+NO_x$). This standard characterizes emissions from current production and achieves the intent of "capping" the exhaust emissions until the catalyst-based standards become effective. The catalyst-based standard is 5 g/kW-hr $HC+NO_x$. Engines complying with this standard will be phased-in over the 2007-2009 time frame at a rate of: 45%–75%–100%. These percentages are based on the manufacturer's annual sales. The phase-in was incorporated to provide manufacturers flexibility to develop and introduce cleaner engines over a three-year period.

In order to keep the emission control system functioning properly and safely, 2007 and later inboard and sterndrive marine engines meeting the 5.0 g/kW-hr $HC+NO_x$ emission standard are to be equipped with an on-board diagnostics marine (OBD-M) system. The OBD-M system will be responsible for monitoring the catalyst, oxygen sensor, fuel system, and comprehensive components (sensor and solenoids). These requirements also provide manufacturers flexibility, with respect to component monitoring strategies and fault code/communication formatting, while still maintaining the desired effectiveness. In case of malfunction, a light or other indicator would be illuminated or activated. If required by the Executive Officer, misfire monitoring will be required on 2009 and later engines. The "misfire monitoring" requirement is subject to Executive Officer approval and shall be based on the need to protect the catalyst.

C) Board Hearing Resolution – Directing Project

To support the proposal for establishing the inboard/sterndrive emission standards, staff successfully demonstrated in a laboratory setting that catalysts and closed-loop fuel systems were feasible and cost-effective. However, industry had two main concerns: 1) excessive heat from a catalyst and 2) water damaging the emission control components. In response to industry's concerns, the Board agreed to undertake a more thorough study of the technology. Board Resolution 01-23 contains the following pertinent paragraphs:

> It is necessary and proper that ARB shall undertake a joint developmental in-water testing program in conjunction with U.S. EPA, U.S. Coast Guard, members of the National Marine Manufacturers Association and manufacturers and suppliers of emission control equipment, in order to demonstrate the safeness and durability of catalysts when used in a marine environment. This program shall include vessel operation in both fresh and salt water; and
>
> It is necessary and proper that ARB staff shall address the Board in 2003 and 2005 to report the findings of the in-water testing program, other related technological developments, and an assessment of the overall feasibility of the regulatory requirements – including the stringency of the emission standards – as well as providing industry the opportunity to present their own assessment of these issues to the Board, and in such reviews staff may consider additional information in order to assist the Board to determine whether it needs to re-evaluate the regulatory requirements.

Following approval of the inboard/sterndrive regulations, staff began the work effort to conduct the testing program. Because of various unexpected delays, the project took considerably longer to complete; thus, the report that was anticipated in 2003 was re-scheduled to 2004. Also, because of budget constraints, vessel operation was limited to fresh water operation.

III. On-Water Demonstration Project

A) Overview and Aim of Project

In August 2002, the Southwest Research Institute (SwRI) commenced work on a project entitled "Development of Low Emission SD/I Boats" ("SD/I" refers to the types of boats; namely sterndrive and inboard boats). As stated in Resolution 01-23, the intent of the project was to demonstrate the safeness and durability of catalysts.

Along with ARB's financial contribution, members of the National Marine Manufacturers Association provided boats and engines, members of the Manufacturers of Emission Controls Association provided the emission control devices, and the United States Coast Guard provided the personnel to operate the boats until the desired 480 hours[1] of "on water" use had been accumulated. As mentioned, SwRI was contracted to conduct the test program, which included fabricating new exhaust systems and sampling the exhaust emissions.

B) Description of Test Vessels

There were four test vessels in the project. The 5.7-liter (L) displacement engine was selected for three of the boats because it is the most popular engine with inboards and sterndrives. Because this test program was to study catalysts, not engines, using the same engine helped to streamline the efforts towards optimizing the engine calibrations. However, a 4.3L engine was also included because such engines are used in entry-level inboard/sterndrive boats. In an attempt to sample a variety of inboard and sterndrive pleasurecraft, the following vessel types and engines were selected. Table 1, below, describes the differences.

Table 1.

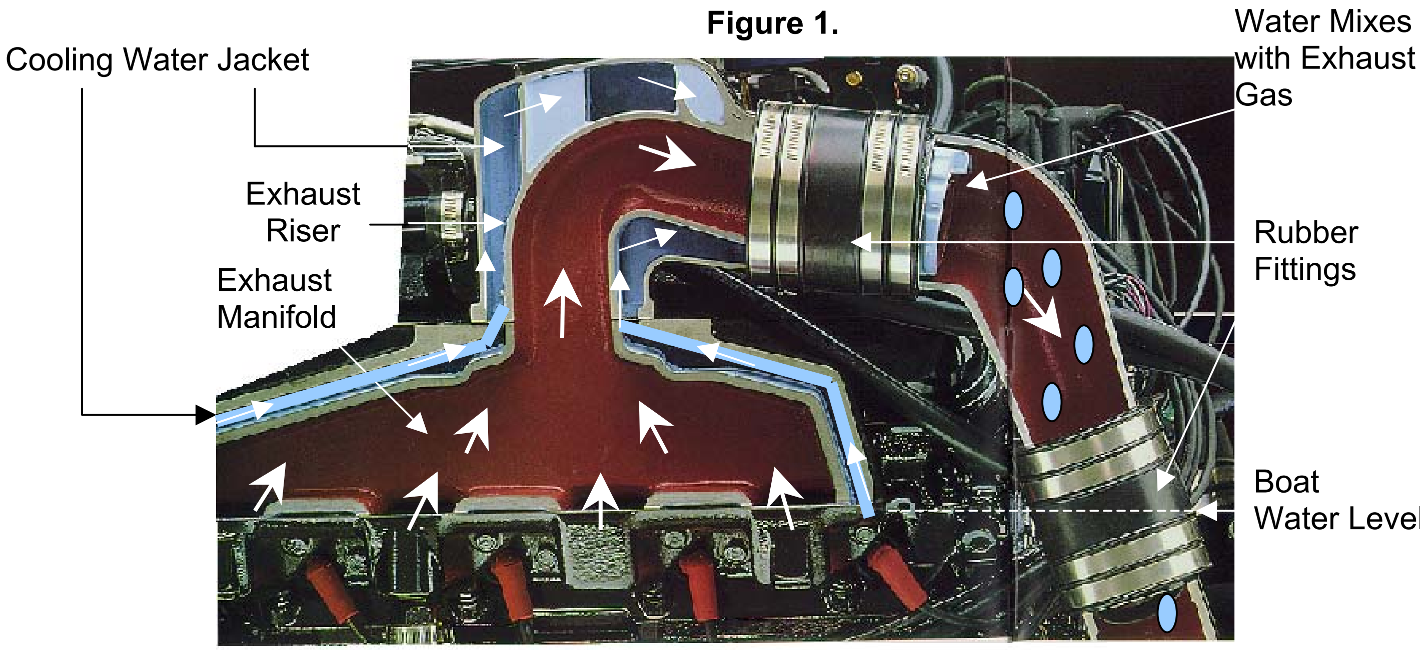
Boat Model	Typical Use	Vessel Type	Engine Type and Displacement
Malibu Wakesetter	Ski Boat	Inboard	V-8 / 5.7L
MasterCraft Maristar	Cruiser	V-drive	V-8 / 5.7L
Sea Ray 220	Cruiser	Sterndrive	V-8 / 5.7L
Sea Ray 190	Cruiser	Sterndrive	V-6 / 4.3L

[1] 480 hours of "on water" operation was chosen because in the inboard/sterndrive regulations, 480 hours is the "useful life" period for compliance testing.

C) Fabrication of Catalyst-Equipped Exhaust Systems

In current inboard and sterndrive designs, water is circulated through the exhaust manifold to provide cooling. Water is also mixed with the exhaust gases for the same reason. Figure 1, below, is a cutaway image of a typical inboard/sterndrive exhaust system. The "red" areas (with the large white arrows) show the exhaust flow; the "blue" areas (small arrows) and droplets respectively show the cooling water's passages and its mixing with the exhaust gases.

Figure 1.



The practice of mixing water with the exhaust gases has been the main technical issue with regards to applying three-way catalysts and feedback air-fuel controls to these engines. Specifically, the concern is "water reversion," whereby given the right circumstances, sea or lake water can travel upstream in the exhaust system. This was a concern because it was thought that water could potentially damage the emission control system. However, SwRI was able to show (based on results from a previous SwRI project) that water in the exhaust/engine was primarily due to condensation, not reversion. By controlling cooling water with a thermostat, condensation problems were largely resolved. For the "Development of Low Emission SD/I Boats" project, a thermostatically controlled cooling system with a water-jacketed exhaust system was used on each of the four engines. Also, because water is commonly mixed with the exhaust gases for cooling purposes, the catalysts and oxygen sensors were placed well upstream of the exhaust gas/water mixing point.

Because it allows for more room on deck, inboard and sterndrive engine compartments are often designed to fit closely around the engine. Such was the challenge in fabricating the new exhaust systems; i.e., making them fit within the confines of the existing engine compartment space. SwRI met the challenge and successfully engineered the catalyst-equipped exhaust systems to neatly fit. The following images are of the exhaust system fabricated by SwRI for a 5.7L engine.

Figure 2 shows the new exhaust system mounted on the engine as the developmental work was in progress in the test cell (i.e., the actual catalyst was not yet installed at this point and thus, only its "location" is shown). Comprised of four sections, the exhaust gases from the engine exit via the exhaust manifold, then are routed upward through a new C-shaped riser. The exhaust gases then enter, pass through the catalyst, and exit through a new water-jacketed exhaust pipe.

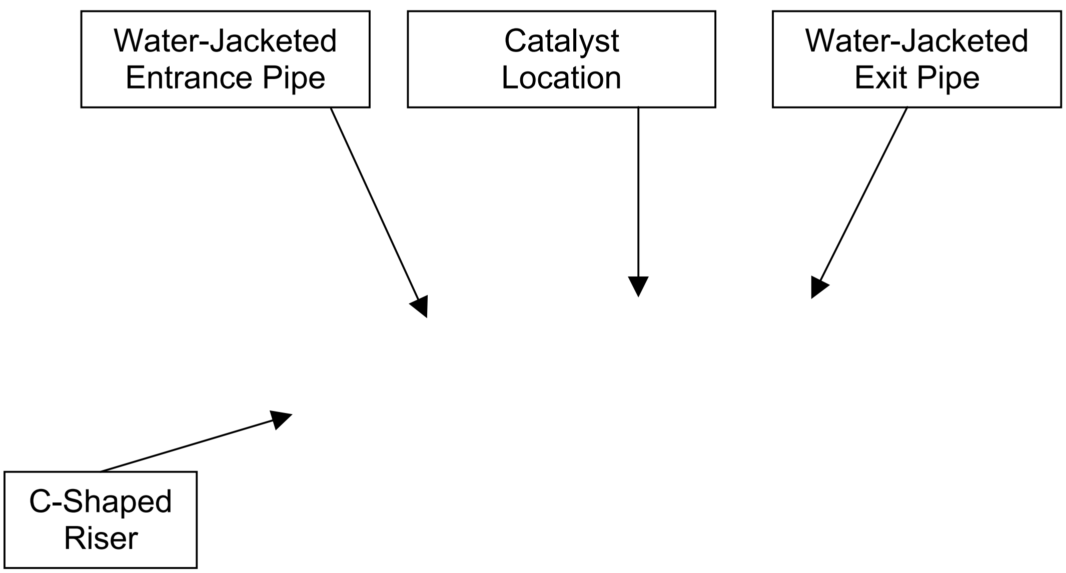


Figure 2.

Figure 3 shows the completed new exhaust system, with the catalyst installed.

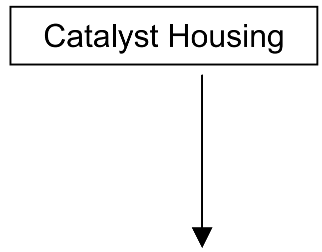


Figure 3.

D) Baseline Calibrations and Emission Testing

A 5.7L and 4.3L engine were used for initial developmental efforts. Specifically, these efforts included developing closed-loop calibrations (i.e., mapping the ignition timing, optimizing the engine controller’s software settings, etc.) and analyzing the performance of various types of catalysts (both metallic and ceramic substrates). Once optimal settings and calibrations were determined, the work to modify the uncontrolled boat engines proceeded.

Zero-hour baseline emissions for each engine were measured while exercising the engine over an established five-mode steady-state certification test cycle for spark-ignition marine engines. Table 2, below, compares the emissions from the uncontrolled development engines with the baseline emissions of the controlled boat engines. On average, $HC+NO_x$ emissions on the 5.7L engines were reduced by 80 percent. On the 4.3L engine, the $HC+NO_x$ emissions were reduced by more than 85 percent.

Table 2.
Exhaust Emission Comparisons

Uncontrolled vs. Baseline Controlled	Brake-Specific Emissions (Grams per Kilowatt-Hour)			
Boat / Engine	HC	NO_x	$HC+NO_x$	CO
5.7L Uncontrolled Engine	5.44	6.68	12.12	193.0
5.7L Baseline Controlled-Malibu Wakesetter	1.72	0.95	2.68	99.6
5.7L Baseline Controlled-MasterCraft Maristar	1.79	0.57	2.37	84.8
5.7L Baseline Controlled-Sea Ray 220	1.82	0.51	2.33	74.2
4.3L Uncontrolled Engine	4.94	11.67	16.61	110.8
4.3L Baseline Controlled-Sea Ray 190	1.90	0.48	2.38	106.3

Below in Figures 8, 9, and 10 are images of the catalyst-equipped engines, installed in two of the boats' existing engine compartments.

Malibu Wakesetter

Engine Compartment Closed **Engine Compartment Open**

Figure 8.

Figure 9.

MasterCraft Maristar

Engine Compartment Open

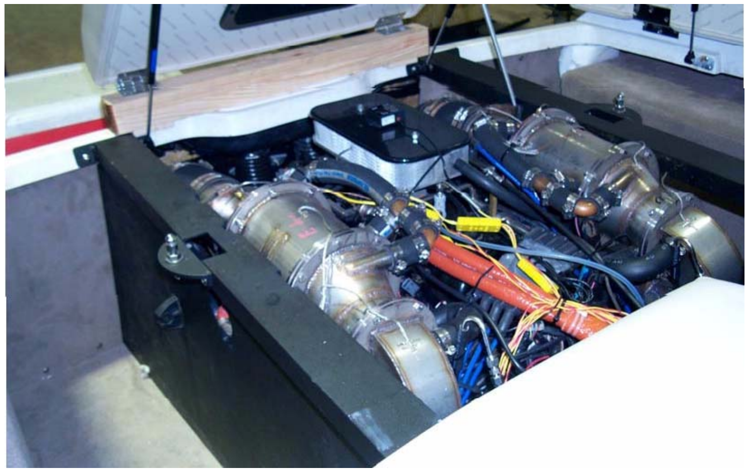


Figure 10.

E) 480-Hour On-Water Accumulation

Figures 11 and 12 below show images of these two catalyst-equipped boats operating on the water for the first time.

Figure 11. **Figure 12.**

The completed boats were transported to Canyon Lake, Texas, for the "on-water" portion of the test program, which was the accumulation of 480 hours of use. Members of the local United States Coast Guard Flotilla contributed in this effort, beginning in December of 2003 and finishing in September of 2004.

Periodic “on-water” emission testing was conducted using a portable dilution system that drew a sample of raw exhaust, and diluted that sample with ambient air. Sample bags were filled with exhaust gases and transported to SwRI for analysis. This type of analysis is not as rigorous as “in laboratory” testing, but was essential to ensure the emission controls and devices were operating properly.

The on-water emission testing during the 480-hour accumulation period confirmed that the emission control system was operating properly and safely without incident. However, it should be noted that some mechanical problems did occur, which were not catalyst related. The V-drive unit on the MasterCraft boat developed a leaky seal, causing the oil to run out. The propeller on the Malibu boat encountered a log and became bent beyond repair; thus, requiring replacement. The Sea Ray 190 also developed a “hot-start” problem. This was solved by replacing the ignition coil and the high tension lead to the distributor.

The engines in the Malibu and MasterCraft boats also became “hydro-locked” during the test program because of leaking and cracked aftermarket exhaust manifolds. Hydro-locking is a condition in which one or more engine cylinders fill with water. Because the water cannot be compressed, the engine can no longer rotate internally. Figure 13, below, shows a close-up image of exterior cracks (lengthwise, in the marked areas) in the exhaust manifold from the MasterCraft boat. Similar cracks inside the manifolds leaked water into the cylinders, causing the problem.

Cracks in Exhaust Manifold

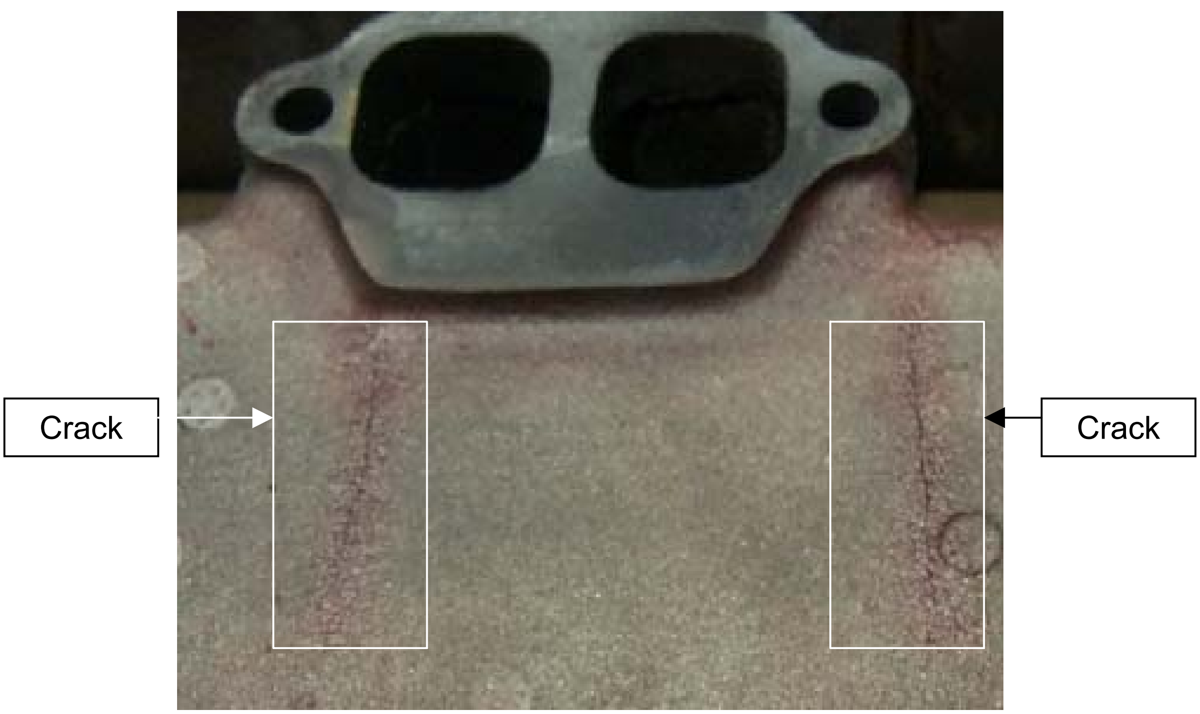


Figure 13.

Hydro-locking can exert excessive stress on connecting rods when the operator attempts to start an engine with water in one or more cylinders. Rather than risk engine problems later on, the engines' connecting rods in the cylinders where water was found were replaced. While the engine was apart, the catalysts were inspected and no signs of failure or damage were observed.

The accumulation of 480 hours of operation over a period of months (as was done in this project) is not typical; on average it takes years to reach (the test period (useful life). Nevertheless, because two of the four engines developed cracked manifolds, suggesting overheating, staff has investigated possible explanations for this development.

- The engines were calibrated to operate at stoichiometry, which is leaner than uncontrolled calibrations, and could have resulted in periods of higher combustion and exhaust gas temperatures.
- Generally, the thermostat in the cooling system maintained an outlet temperature at 185º F. This was slightly higher than normal (to guard against condensation), but under the 200º F safety threshold set by the U.S. Coast Guard. Therefore, it is unlikely the thermostat setting contributed to the manifolds cracking.
- The exhaust manifolds that failed were used on the Malibu and MasterCraft engines only had partial water-jacketing, while the exhaust manifolds on both Sea Ray engines were completely water-jacketed. Neither of these fully jacketed manifolds developed cracking or hydro-locking conditions.

Partial water-jacketing creates larger temperature gradients throughout the manifold, which increases the likelihood of cracking. The use of fully water-jacketed exhaust manifolds for future catalyst-equipped engines will diminish the occurrence of cracking manifolds.

F) Final Emission Testing

Upon successful completion of 480 hours of "on-water" operation, the boats were returned to SwRI. The engines were removed from the boats and installed in a test cell for emission testing. Compared to 0-hour baseline testing, some deterioration of the emission levels is expected after 480 hours of use. Staff was very pleased to learn however, that although demonstrating compliance to the 2007-2009 catalyst-based standards was not the aim of this project, all three 5.7L engines remained under the 5.0 g/kW-hr standard for HC+NO_x. Tables 3, 4, and 5, below, compare the 0-hour and 480-hour emission results.

Table 3.

5.7L Malibu Wakesetter	Brake-Specific Emissions (Grams per Kilowatt-Hour)			
	HC	NO_x	$HC+NO_x$	CO
0-hour	1.72	0.95	2.68	99.6
480-hour	2.07	1.68	3.75	117
Percent Change	20%	76%	40%	17%

Table 4.

5.7L MasterCraft Maristar	Brake-Specific Emissions (Grams per Kilowatt-Hour)			
	HC	NO_x	$HC+NO_x$	CO
0-hour	1.82	0.54	2.36	86.5
480-hour	1.71	0.96	2.67	101.6
Percent Change	-6%	78%	13%	17%

Table 5.

5.7L Sea Ray 220	Brake-Specific Emissions (Grams per Kilowatt-Hour)			
	HC	NO_x	$HC+NO_x$	CO
0-hour	1.82	0.51	2.33	74.2
480-hour	1.53	0.93	2.46	92.5
Percent Change	-16%	82%	6%	25%

The 4.3L engine in the Sea Ray 190 exceeded the catalyst-based standard slightly. Although further investigation on the engine will be conducted to explain the reason(s) for the higher emission levels, SwRI has already determined that excessive fuel was being delivered to one engine bank; and one cylinder on that bank had low compression. The excessive fuel would explain the increase in HC emissions. The low compression in one of the cylinders would result in incomplete combustion, which would also increase HC emissions. However, more importantly, incomplete combustion also results in increased oxygen levels in the exhaust, which would significantly reduce the catalyst's NO_x reduction efficiency.

No cause for the excessive fuel and low compression has been reported by SwRI at this time. However, these "problems" do not appear to be related to the installation of the catalysts. It should also be noted that despite the conditions experienced by this engine, the $HC+NO_x$ emissions were still well below the uncontrolled level of 16.61 g/kW-hr; suggesting that the catalyst was still functioning efficiently.

Table 6.

Sea Ray 190 4.3L	Brake-Specific Emissions (Grams per Kilowatt-Hour)			
	HC	NO_x	$HC+NO_x$	CO
0-hour	1.90	0.48	2.38	106.3
480-hour	2.97	2.77	5.75	115.9
Percent Change	57%	479%	142%	9%

G) Assessment of Emission Controls

With the goal of demonstrating safeness and durability of catalysts, the project was successful. There were no instances of fire or excessive heat, and the results from both the on-water and in-laboratory exhaust sampling show that catalysts are robust in the marine environment.

Figures 14 and 15 below compare the inlets and outlets of the catalysts from the engine used in the Sea Ray 220 boat. These, as well as the other catalysts, were not fractured or damaged during the test program.

Left and Right Bank Inlets

Figure 14.

Left and Right Bank Outlets

Figure 15.

Another notable success was the upstream oxygen sensors. These prototype sensors were designed with a shrouded tip, to make them less prone to water damage. Throughout the course of the on-water accumulation, these sensors did not require replacement. It should be noted that the oxygen sensor was upstream of the catalyst, not downstream. Manufacturers have raised issues with the durability of downstream sensors in the marine environment. Staff believes the thermostatic control of cooling water, which reduces condensation, should alleviate the problem.

IV. Other Related Issues

A) U.S. EPA Proposed Rulemaking

In August 2002, U.S. EPA announced a proposed rulemaking aimed at controlling evaporative emissions from spark-ignition marine engines (including inboards, sterndrives, personal watercraft, and outboards). According to their emission inventory modeling, spark-ignition marine engines were responsible for 108 tons per day (tpd) of evaporative emissions in 2000, nationwide. By 2020, these emissions are projected to increase to 114 tpd. Evaporative emissions are primarily hydrocarbon emissions. For comparison, over the same time frame hydrocarbon exhaust emissions from these marine engines are projected to drop from 708 to 284 tpd because of the regulations for exhaust emissions.

The U.S. EPA is considering reducing diurnal emissions, fuel tank permeation, and fuel hose permeation. The proposed standards represent more than a 25 percent reduction in diurnal emissions and a 95 percent reduction in permeation from both tanks and hoses. At the time this proposal was released, U.S. EPA did not propose exhaust emission standards for inboard and sterndrive engines. Instead, they wanted to collect more information and investigate further the application of catalysts; which would not only apply to inboards and sterndrives, but also personal watercraft and outboard engines.

Staff anticipates a final rulemaking from U.S. EPA by late 2004 or early 2005.

B) Carbon Monoxide Emissions

Neither the federal nor California regulations for spark-ignition marine engines contain emission standards for CO. Both control measures focused on reductions of ozone-forming emissions; i.e., HC and NO_x. However, as an added benefit from the improved fuel calibrations and the conversion from two-stroke to four-stroke technology with personal watercraft and outboard engines, CO emissions are expected to decrease. These reductions are expected to decrease further with the introduction of inboard and sterndrive engines meeting the catalyst-based standards.

Recent studies have been undertaken to study CO exposure in the recreational marine environment. A prominent study, led by the National Institute for Occupational Safety and Health,[2] took place at Lake Havasu, where recreational boating is quite popular. CO monitoring equipment was placed in various locations, both on boats and on land near the shore. NIOSH recommends CO levels not exceed 35 parts per million (ppm), as measured over a time-weighted average during an eight-hour workday with a maximum exposure of 200 ppm. Over a holiday weekend, CO concentrations were measured in the 100-200 ppm range. These measurements were taken "on shore" where the Lake Havasu employees and police personnel work. They also measured CO levels increasing at a rate of 20-30 ppm per hour when the wind began to die down.

There have also been prominent news stories about people becoming ill and dying due to CO exposure after engaging in an activity known as "teak surfing." In teak surfing, a person rides the "wake" that is caused by the propulsion of the boat through the water. This is done at slow speeds, with the person in the water following very closely behind the back of the boat. The back of the boat is also where the exhaust gases are routed; thus, putting the teak surfer at risk.

The U.S. Coast Guard and the boating industry have been holding workshops to discuss CO exposure. While recognizing that both propulsion engines and auxiliary engines (e.g., generators) need to emit low levels of CO, there is a strong need to educate the boating community about the hazards of those activities that place people in close proximity of the exhaust. At these meetings, U.S. EPA has announced they are working towards proposing CO emission standards for spark-ignition marine engines that will reduce emissions by approximately 50 percent. The reduction in CO observed from the 5.7L engines tested in our program was approximately 50 percent. The catalysts did not lower CO emissions from the 4.3L test engine.

C) Industry's Concerns

Since the 2001 inboard/sterndrive rulemaking, the boating industry has raised three issues with staff. In 2003, the National Marine Manufacturers Association approached staff with a request to amend the phase-in of the catalyst-based standards. Instead of a three-year phase-in (45%–75%–100%) during model years 2007-2009, industry requested we consider 100 percent compliance in 2008. A statewide inventory analysis for 2010 and 2020 shows that a full implementation alternative in 2008 would not have a negative impact, although certain local air pollution control districts have counted on the reductions from catalyst-based standards taking effect in 2007.

Another request from industry is to amend the regulations to continue to allow corporate averaging beyond 2008. Currently, engines over 500 horsepower are unregulated through 2008. Industry would like to be able to certify non-catalyzed

[2] (NIOSH – a Federal agency that is part of the Centers for Disease Control and Prevention)

engines over 500 horsepower by averaging their emissions with the emissions from their controlled (i.e., catalyst-equipped) engines. Manufacturers believe that because the over 500 horsepower engines comprise a very small percentage of sales, their uncontrolled emissions will be more than offset by much lower emission levels from the catalyst-equipped engines; and that this flexibility will not compromise the air quality benefits of the inboard/sterndrive regulations.

Lastly, industry has requested to phase-in the on-board diagnostic requirements. The first phase, to begin in 2008, would not include catalyst monitoring. Catalyst monitoring is typically done with two sensors: pre- and post-catalyst. Industry has concerns about post-catalyst sensors surviving in the marine environment. Following an industry-proposed Technology Review in 2010, the second phase, which would include catalyst monitoring, would be delayed until 2012.

Staff is suggesting meeting with industry to discuss these issues in further detail and, if warranted, returning with its findings for the Board's consideration next year.

V. Conclusion

The "on-water" demonstration project successfully demonstrated that catalysts are safe in the marine environment. There were no heat-related safety issues that arose during the 480 hours of operation (cumulatively, over 1,900 hours). The cooling system fabricated by SwRI kept the skin temperature of engine components below 200 degrees Fahrenheit, which is the threshold to which the U.S. Coast Guard requires and industry complies.

Durability was also demonstrated. The catalysts continued to function efficiently. Three of the four engines measured below California's 5.0 g/kW-hr $HC+NO_x$ standard after the 480 hours of operation. The engine that exceeded the standard by 15 percent was determined to have developed low compression in one of its cylinders; leading to less-than-optimal combustion and higher-than-normal HC emissions. Nevertheless, the $HC+NO_x$ emissions were still much lower than uncontrolled levels. Another important display of durability was the fact that the exhaust gas oxygen sensors did not require replacement throughout the project.

Because of the successful outcome of the test program, staff believes that the overall feasibility of the regulatory requirements has been reinforced. Staff therefore recommends continued support of the catalyst-based emission standards for inboard and sterndrive engines. During the next year, staff can discuss with industry their concerns and requests to amend the regulations and report back to the Board in 2005.